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RELIABILITY-BASED DESIGN OF OVERHEAD TRANSMISSION STRUCTURES - AN OVERVIEW

Report No. 91-233-K

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ABSTRACT

In this report three Reliability-Based Design (RBD) methods for overhead transmission structures are reviewed. The first RBD was developed by the International Electrotechnical Commission (IEC), the second one by the Electric Power Research Institute (EPRI) and the third by the American Society of Civil Engineers (ASCE). The similarities and the differences between these methods are critically reviewed and comparisons are made. Also discussed is a proposed reliability-based transmission line design method for Ontario Hydro.

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EXECUTIVE SUMMARY

RELIABILITY-BASED DESIGN OF OVERHEAD TRANSMISSION STRUCTURES - AN OVERVIEW

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Application of reliability-based methods to the design of transmission structures has been gaining widespread recognition as a viable alternative to the present deterministic approaches. This is mainly due to the potential of the reliability-based methods for better assessment of transmission line reliability.

The basic and important difference between the two methods is that the reliability-based method can more effectively account for the variations in the design parameters such as wind and ice loads. A typical example, by which the limited ability of the current design methods can be explained, is the design of wood pole power lines where the weather related loads and the strength of poles exhibit relatively wide variations. These variations in load and strength cannot be effectively accounted for with the current deterministic methods.

During the past decade or so Ontario Hydro has been involved in the evaluation and development of Reliability-Based Design (RBD) methods applied to transmission structures. At present, several RBD methods are available for transmission structures. This report contains a critical review of the three RBD methods, proposed by the Electric Power Research Institute (EPRI), International Electrotechnical Commission (IEC) and the American Society of Civil Engineers (ASCE). Even though the basics of these methods are not very different, the procedures to apply them to the design of transmission structures are significantly different.

In the IEC method, the transmission line is considered to be a series system consisting a number of components such as insulators, tangent towers, angle towers, foundations and conductors. The failure of any of these components can cause the failure of the system (i.e., loss of power). The objective is to design this system for a specific reliability level, considering the variability of as many parameters (such as loads and strengths) as possible. The method also proposes a strength coordination scheme by assigning a sequence of failure for the line components.

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The EPRI method, which applies Load Resistance Factor Design (LRFD) approach to develop design procedures, is a slightly simplified version of the IEC method. The basic difference between the two approaches is that the IEC method controls the reliability of the entire line while the EPRI method indirectly controls the line reliability by controlling the reliability of individual structures. This is achieved by means of a factor which controls the relative component reliabilities and thus the sequence of failure.

The ASCE method, like the EPRI method, also indirectly controls the line reliability by controlling the individual component reliabilities. This is done by means of global reliability and component reliability factors. The component reliability factor is also used to control the preferred sequence of component failure.

As proposed in the IEC method, treating the transmission line as a system is probably the most effective way to design. However, the approximations used in the other two methods may simplify the design calculations.

All the three methods, in general, use available weather data to calculate design wind, ice and wind-on-ice loads. However the procedure used by each method is significantly different from the other. It is difficult to assess the relative merits of these methods unless these are applied to typical situations using a common data base. Hence, there is a need for more work to be done to improve the quality and quantity of load data.

The target reliability in IEC method is given in absolute terms, while in the other two methods it is given in relative terms. Even though the absolute target reliability may be useful, it is very important to know the relative reliability of the new design compared with the existing ones. It should be noted that the assessment of absolute reliability is extremely difficult.

In summary, the following remarks could be made about the RBD methods reviewed in this report:

- The IEC method directly calculates the line reliability while the other two methods do it only indirectly.
- The IEC method gives reliability in absolute terms while the other two methods provide reliability related to existing lines.
- It would be useful to compare the results of these methods if the procedures to calculate climatic loads are made more uniform.

The reliability-based design method can provide better quantitative estimate of system reliability which in turn may translate into more economical design.

To compensate for the inadequacies in the three RBD methods reviewed in this report, it would be useful to develop a modified RBD method. This proposed RBD method will incorporate the beneficial features of the three current RBD methods and include items that are unique to Ontario Hydro's current design practices.

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To Dr. M.S. Nashid
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RELIABILITY-BASED DESIGN OF OVERHEAD TRANSMISSION STRUCTURES - AN OVERVIEW

1.0 INTRODUCTION

The concept of applying reliability-based methods to the design of overhead transmission structures is widely considered as a viable alternative to the current deterministic methods. The basic and important difference between the two methods is that the reliability-based method can more effectively account for the variations in the design parameters such as wind and ice loads. In the past decade or so significant advances have been made in developing procedures to apply reliability-based methods to electric power systems.

A typical example, by which the limited ability of the current design methods can be explained, is the design of wood pole power lines where the weather related loads and the strength of poles exhibit relatively wide variations. These conditions in load and strength cannot be effectively accounted for with current deterministic methods.

Reliability-based methods can be used in such situations where one or more of the design parameters are random variables. In these cases, reliability-based techniques provide better assessments of system reliability by accounting for the variability in design parameters. In deciding whether or not a reliability-based method should be applied to a given situation, the first step is to study the various parameters to be used in the analysis/design. If the distribution of these parameters exhibit relatively significant variations, then the application of the reliability-based methods may be advantageous.

Reliability-based techniques are being widely used in the design of large civil structures such as buildings and bridges. Since transmission lines are more vulnerable to widely extreme loads and other critical situations than the civil structures, the application of reliability-based methods is even more important. The greater vulnerability of the transmission lines is mainly due to the importance of each of its components and its relatively greater length. For example, the failure of a tower foundation, insulator or conductor can lead to the sudden failure of electric power transmission lines. The chances of having relatively weak components exposed to extreme climatical loads could increase with the length of a transmission line. To realistically account for these unknowns and variables that influence the operation and reliability of a transmission line, a reliability-based design method is more suitable. The reliability-based design method can provide better quantitative estimate of system reliability which in turn may translate into more economical design.

In the last decade or so, various technical groups and committees have been working to develop reliability-based methods for the design of transmission structures. Among them, the Electric Power Research Institute (EPRI) /1/ and the International Electrotechnical Commission (IEC) /2/ are the leading technical bodies devoting considerable effort and time to promote reliability-based design methods. The American Society of Civil Engineers (ASCE) also has developed a design procedure /3/ for transmission structures. As will be seen later in the report, even though the basics of these methods are not very different, the procedures to apply these methods to the design of transmission structures are significantly different.

In this report, the basics of reliability-based design methods as applied to simple structural components will be briefly explained along with some detailed description of the three RBD methods. The differences between these methods will also be discussed in detail. An alternative reliability-based design method is proposed for transmission line design in Ontario Hydro.

2.0 BASICS OF RELIABILITY-BASED TECHNIQUES

The application of reliability-based techniques to structural system can best be explained by a graphical representation. Hypothetical variations for distributions of load and strength for a single structural component (e.g. a pole) can be symbolically represented as shown in Figure 1. A detailed discussion can be found in Appendix D. The overlap of these two distributions, a region in which the load may exceed the strength, indirectly represents the probability of failure, or in other words, is an indication of the reliability of the structural member. As the overlap increases, the probability of failure increases and hence the reliability decreases.

It can be shown that not only the relative positions of the two distributions affect the level of reliability, but also the type of variability in the distributions (i.e., the shape and skewness of the curves). In Figure 2, two hypothetical load distributions with identical mean values but of different shapes are used in the calculation of probability of failure. By comparing the relative sizes of the shaded areas in Figure 2, which indirectly represent the probabilities of failure, it can be seen that the shape of the distributions do affect the reliability level.

In real situations, a structural component is invariably subjected to more than one loading condition. The procedure for deriving the probability of failure of a simple structural component subjected to more than one load /4/ will now be graphically explained by reference to Figure 3. The three loading situations considered are wind, ice and wind-on-ice. The derivation of wind load distribution on the structural component is graphically shown in Figure 4, where the wind speed and component size are random variables. Referring to Figure 4, the first step is to establish, from available information, the distributions for wind speed (Figure 4a), component length (Figure 4b) and depth (Figure 4c) along with a relationship to calculate the wind load on the component (Figure 4d). The next step is then to use a simulation technique or any other method to derive the probability density distribution for the wind load on the component (Figure 4e). The procedure illustrated here could be used in any situation, provided the necessary information on the distributions and a mathematical relationship between them are available.

Even though the calculation of probability of failure or reliability explained here is with respect to a single structural member, in reality the systems are made of a large number of components where, in general, a set of "critical" members decides the system reliability. The reliability analysis of a system consisting of a large number of components and subjected to more than one loading condition is more complex. In

analyzing such a system, one should also consider the correlation between various loading events, the extent of weather related loads, the effect of terrain, etc.

In general, the following steps, shown schematically in Figure 5, are needed for applying the probabilistic method:

1) Establish statistical load and strength distributions from available data.
2) Establish statistical distributions of key physical dimensions of the system to be analyzed.
3) Perform a detailed analysis of the system to identify its response to applied loads.
4) Identify various potential failure modes.
5) Using the information generated in steps 1 to 4 and appropriate calculation techniques/4/, assess the probability of failure or reliability.

3.0 VARIABILITY OF DESIGN PARAMETERS

In this section, some typical parameters will be briefly discussed to show the importance of the probability methods which will account for the statistical variability of these parameters. The parameters shown in Figures 6 through 8 are only some of the typical ones used in the design of transmission lines. The type and degree of variability of any parameter can be, in general, represented by established statistical distributions. The statistical properties such as mean, standard deviation and coefficient of variation of these parameters can be calculated from the data population. The values of the mean, standard deviation and COV for the three parameters, shown in Figures 6, 7 and 8 are tabulated below:

Parameter	*Mean*	*STD. Dev.*	*C.O.V.*
Wind Load	1700 lb.	512 lb.	30%
Pole Strength	5350 psi	1170 psi	22%
Insulator Strength	2335 lb.	332 lb.	14%

The above statistical properties are normally used in the current design process as follows, either to calculate the design "load" or "strength":

Design Wind Load = mean wind load + n_1 (standard deviation of wind load)
Pole Strength = mean pole strength - n_2 (standard deviation of pole strength)
Insulator Strength = mean insulator strength - n_3 (standard deviation of insulator strength)

The values of n_1, n_2 and n_3 are chosen to meet the safety and reliability requirements of the components or systems being designed. This procedure, which could be appropriately called "semi-probabilistic" technique, partially takes into account the effect of parameter variability. However, the effects of interaction between the strength and load variables (Figure 1), including that of the distribution shape, are not explicitly considered. Hence the proposed probability method, which fully takes into consideration the variability of the parameters, is an important and significant forward step in designing of transmission systems.

It is not always necessary that each and every parameter be treated as a statistical variable. The first step in deciding whether or not a parameter should be treated statistically is to compare its COV with that of other parameters considered in the calculations. By comparing the COVs of all the parameters the designer should be able to exclude the ones that need not be treated statistically. The exclusion procedure will help to minimize the time and cost to apply probabilistic methods to complex systems without sacrificing the accuracy of the results.

4.0 PROBABILITY DISTRIBUTION OF TYPICAL WEATHER-RELATED LOADS

The application of probabilistic methods requires that the data be available in suitable statistical formats. In many cases, the available information is not sufficient for direct use in the probabilistic methods. For example, in the case of structural loading on transmission lines, while the amount of wind data available is considerable, the data on ice and wind-on-ice are not adequate. If the existing information is not available in a statistical format, then it should be transformed by suitable analytical techniques. Procedures for transforming weather data into wind, ice and wind-on-ice load distributions are given in /5/.

5.0 APPLICATION OF RELIABILITY-BASED METHODS TO TRANSMISSION STRUCTURES DESIGN

The basics of reliability-based methods discussed in the previous sections will now be applied to the design of transmission structures. For the past several years, the Electric Power Research Institute, American Society of Civil Engineers (ASCE) and the International Electrotechnical Commission have been separately working to develop reliability-based design methods for transmission structures. In this section, the main features of each of these methods will be discussed in some detail. Also discussed will be the similarities and differences between these methods.

Both the ASCE and IEC documents are currently undergoing a thorough review by the international engineering community and an IEEE Task Force/6/. The PMAPS (Probability Methods Applied to Power Systems) International Conference Series, started in 1986, has produced important documents on the RBD methods/7,8/.

5.1 Reliability-Based Method Proposed by the International Electrotechnical Commission (IEC)/2/

5.1.1 *Introduction*

In this method, the transmission line is considered to be a series system consisting of a number of components such as insulators, tangent towers, angle towers, foundations and conductors. The failure of any of these components can cause the failure of the system (i.e., loss of power). The objective is to design this system for a specific reliability level, considering the variability of as many parameters (such as loads and strengths) as possible. The term reliability is defined as the probability of achieving a particular task under a set of conditions for a specific time.

In addition to providing a desired reliability level, the designer should also ensure that security and safety requirements for the system are satisfied. Security is defined as the ability of a system not to have a

complete collapse if a component fails, and safety is defined as the ability of a system not to cause human injury or loss of life.

5.1.2 *Some Main Design Considerations*

The following main factors are considered in assessing the line reliability:

- The effect of actual spans that could be different than the design span, by applying the concept of "use factor".

  "Use factor" is defined as the ratio of stresses due to design load to the limit stresses of a component. For tangent towers, it is virtually equal to the ratio of actual to maximum design spans. It is easy to see that a small use factor implies that the line is subjected to smaller loads than it was designed for and is, therefore, more reliable than was intended.

- The effect of load distribution in the system, by considering the number of components subjected to a critical loading condition.

  This implies that the probability of failure increases as the number of components that are subjected to extreme loading situations increases. This increase in the probability of failure depends on the COV of strength of the component considered and decreases as the COV becomes smaller.

- The effect of strength coordination between components.

  Although, as mentioned before, the goal is the design of a transmission line system, it is possible to make the process more manageable by assigning a preferred sequence of failure to the transmission system components. This will ensure that failure, if initiated, will follow a path that the designer considers less destructive to the system as a whole.

5.1.3 *Design Equation*

The equation for the reliability-based design of transmission structures, in the general Load Resistance Factor Design (LRFD) format, is given below.

$$\phi R_n > \gamma_u E[DL+Q_{RP}]$$

where

γ_u = reduction(or use) factor dependent on span dispersion

$E[\ ]$ = Effect of

DL = Dead Load

Q_{RP} = Extreme loading event at a point corresponding to return period RP (RP Between 50 to 500 years)

R_n = Nominal strength of component

ϕ = $\phi_S \phi_Q \phi_C \phi_N$

and

ϕ_N = Factor related to the number of components under critical load

ϕ_Q = Factor related to the quality of the component during fabrication and construction

ϕ_C = Factor related to the relationship between the actual exclusion limit, R_c, and the assumed value of 10% exclusion limit of structural component,

ϕ_S = Factor related to the strength coordination between components.

The right side of the equation represents the load applied to the line and the left side represents the strength of the line. The balancing of the design equation by choosing appropriate factors is expected to result in a system with the desired reliability

5.1.4 *Climatic Loads*

5.1.4.1 *Wind Load:*

To calculate the wind load, two types of wind data are considered.

- High wind at average of minimum daily temperatures
- Reduced wind (60% of high) at the 50 year return period minimum temperature

Corrections are applied to the wind load to account for the following:

- Wind gust
- Conductor height
- Span length
- Conductor shape

5.1.4.2 *Ice Load:*

In calculating the ice load (without wind) two types of icing are considered.

- Precipitation icing
- In-cloud icing

Three possible sources are considered for obtaining ice data:

- Ice records are available for at least 10 years
- Only maximum ice value is available for a given period
- Maximum yearly ice values can be predicted using models

Corrections are applied to the ice load to account for the following:

- Conductor height
- Conductor shape
- Number of years of data

(Also taken into account are the loading condition due to non-uniform icing on conductor span).

5.1.4.3 *Wind-on-Ice Load:*

The source for wind-on-ice data is the same as in 5.1.4.2. except that the wind speed during ice storms will be considered. The following are the main parameters that will affect wind-on-ice loads on conductors:

- Ice thickness
- Ice density
- Conductor shape
- Wind speed (during ice storms)

5.1.5 *Other Loads*

Other load conditions considered are:

- Construction and maintenance loads
- Security related loads

A detailed account of the IEC method is given in Appendix A.

5.2 Reliability-Based Method Proposed by Electric Power Research Institute/1/

5.2.1 *Introduction*

Almost a decade ago, the Electric Power Research Institute embarked on a research project to develop a reliability-based design method for transmission structures and to establish a data base for wood pole strength. During this project two different approaches were developed for applying the reliability-based methods to design transmission structures:

- β-V method
- Base line method

Both methods apply Load and Resistance Factor Design (LRFD) approach to develop design procedures and both are used for the design of components of the transmission line for a specific reliability level. The Base Line method is in two parts: a) basic base line method and b) the modified base line method.

The design equation can be written in the general LRFD format as shown below:

$$\phi R_n > \gamma Q_n$$

where

Q_n = Nominal load

R_n = Nominal strength,

ϕ = Resistance factor (usually less than one), and

γ = Load effect factor (usually greater than one).

The right side of the equation represents the "load" on the structure and the left side the "strength" of the structure. These are usually referred to as the "factored load" and "factored strength". The various factors should be appropriately chosen to obtain a certain desired structural reliability. The LRFD equation is nothing new to a design engineer because essentially it is a convenient format to choose values of load and strength for designing a reliable structure.

The LRFD equation can be satisfied by any one of the following approaches:

1) Use mean values of R_n and Q_n but choose values for the design factors γ and ϕ to be different than 1.

2) Define R_n at a low enough exclusion limit and Q_n at a high enough return period and use γ and ϕ of 1.

3) Use a combination of the above two methods.

5.2.2 ***β-V Method***

5.2.2.1 *Introduction:*

β-V method is based on the first approach and hence the mean values of load and strength are used in the LRFD equation. β is the reliability index associated with the component and is defined as the ratio of the mean value of the failure function to its standard deviation/1/. The value of β is therefore linked to the probability of failure of the component.

5.2.2.2 *Design Equation:*

The LRFD equation for the **β**-V method is written as:

$$\phi_{\beta,V} R_m > E [\gamma_{\beta,V} Q_m]$$

where

$E[\ ]$ = Effect of

Q_m = The mean value of load

R_m = The mean value of strength,

$\phi_{\beta,V}$ = Resistance factor = $\exp(-\alpha_R \beta V_R)$

$\gamma_{\beta,V}$ = Load effect factor = $\exp(\alpha_Q \beta V_Q)$

β = The reliability index

V_R = The COV of resistance

V_Q = The COV of load

α_R, α_Q = Factors obtained through reliability studies.

The value of β could be related to the life span for which a structure should be designed. The transmission lines are normally designed for at least a period of 50 years. This would correspond to β=3. Values of α equal to -0.75, 0.75, .3 are usually used for calculating γs pertaining to resistance, wind speed and ice load. Note that the β-V design equation is only a function of the mean and COV of load and strength data and does not require information regarding the distribution of these parameters.

5.2.2.3 *Climatic Loads:*

5.2.2.3.1 **Wind Load**

About 20 years of mean yearly fastest mile wind speed data are considered sufficient; if less, necessary corrections should be made to the mean and COV values.

Adjustments are made to the wind load to account for the following:

- Distance between the anemometer site and the line location
- Conductor height
- Conductor shape
- Wind gust

5.2.2.3.2 **Ice Load**

The following sources are suggested for obtaining ice data:

- NESC standard
- ASCE loading guide
- If available use regional historical data

5.2.2.3.3 **Wind-on-Ice Load**

The extreme ice thickness values calculated in (5.2.2.3.2) should be combined with a maximum wind speed that will prevail during ice residency. A default value for ice residency and methods to estimate the maximum wind speed are discussed.

A detailed discussion on this method is given in Appendix B.

5.2.3 *Base Line Method*

The "Base Line" design method is an example of the second approach proposed by EPRI for performing reliability based design, i.e., using resistance at a low exclusion limit and load at suitably high return period. In this approach the following criterion is satisfied.

$$R_5 > Q_{50}$$

The above equation, in which R_5 is the 5% exclusion limit strength and Q_{50} is the 50 year return period load, is considered the base line or reference design case and corresponds to a probability of failure (P_o) of about 0.02. Any other probability of failure can be achieved by changing the factored load or strength using the method discussed below.

5.2.4 *Modified Base Line Method (CG) or ASCE Method*

5.2.4.1 *Introduction:*

The modified base line method attempts to improve the design equation used in base line method, 5.2.3, using appropriate load and resistance factors. The C.G. method has been used by the American Society of Civil Engineers (ASCE) to develop a design document for overhead transmission structures/3/. Hereafter, the method will be referred to as the ASCE Method.

5.2.4.2 *Design Equation:*

The ASCE method of reliability based design involves satisfying the equation:

$$\phi R_s > \gamma Q_{50}$$

In LRFD format, this equation is written as:

$$\phi R_n > E [\gamma_D DL + \gamma Q_{50}]$$

or

$$\phi R_n > E [\gamma_D DL + Q_{RP}]$$

where

$E[\ ]$ = Effect of

Q_{RP} = Extreme loading event at a point corresponding to return period RP

R_n = Nominal strength of component

DL = Dead Load

ϕ = A strength factor containing variables associated with resistance and can be modified to be used for strength coordination.

γ = A load modification factor

γ_D = Dead load modification factor

The ultimate goal is to design components with known reliabilities with respect to a corresponding base line (reference) component. This is achieved by selecting a global reliability adjustment factor (G) and a component reliability adjustment factor (C). The multiplying factors for resistance, ϕ, and load, γ, are determined from values of C and G respectively. Then the target reliability of the component designed is

$$P_f = P_o / (GC)$$

where

P_o = the annual base or reference probability of failure

G = Line (or Global) reliability factor

C = Component Reliability factor.

For example, using C=2 and G=5 in the design of a component will provide a line with a reliability 10 times better than the reference line reliability.

5.2.4.3 *Climatic Loads:*

5.2.4.3.1 **Wind Load**

The fastest mile wind speed is used to calculate the wind load. If the wind data is not available in this format then it should be converted by means of suitable relationships.

Appropriate corrections are applied to the wind load to account for the following:

- Wind gust
- Exposure and height
- Conductor shape
- Span length

5.2.4.3.2 **Ice Load**

The following data sources could be used to calculate ice loads on conductors:

- NESC district map/9/
- ASCE guide/10/
- Study of local historic storm data

Using either one of these data sources, ice load corresponding to a return period of 50 years should be calculated.

5.2.4.3.3 **Wind-on-Ice Load**

The extreme ice thickness values calculated in (5.2.4.3.2) should be combined with a wind speed that will prevail during ice residency. The recommended wind speed is equal to 0.4 times the wind speed for a return period of 50 years

5.2.4.4 *Other Loads:*

Other load cases due to construction, maintenance and security are also considered. A detailed description of the method is given in Appendix C.

6.0 DISCUSSION OF IEC, Ø-V AND ASCE METHODS

6.1 Introduction

In this section, the IEC, Ø-V and ASCE methods will be summarized and compared to highlight their key points.

The basic objectives of these methods are to outline reliability based design procedures, in general, to account for the statistical variability in design parameters such as load on the line and strength of the structures and to obtain a uniform structural/system reliability. The IEC method is more comprehensive and treats the line as a system while the other two methods consider only individual structures of the line. In other words the IEC method controls the reliability of the entire line while the other two methods indirectly control the system reliability by controlling the reliability of individual components. The methods also differ in the techniques used to calculate/estimate the various load and strength factors required for the design.

In this section, first the key points of each method will be listed separately before they are combined for comparison. The key items that will be discussed for each method are itemized below.

1. Basic concepts
2. Design equations
3. Climatic loads
   - Wind load
   - Ice load
   - Wind-on-ice load
4. Target reliability
5. Other Aspects
   - Construction, maintenance and security loads
   - Effect of different span lengths

6.2 Basic Concepts

IEC Method: This method estimates the reliability of an entire line by subjecting it to a single climatic event such as wind, ice or wind-on-ice. The method proposes a strength coordination scheme by assigning a sequence of failure for the line components.

Ø-V Method: In this method, the reliability of a line is indirectly controlled by direct control of the reliability of its components. This is achieved by means of a factor which controls the relative component reliabilities and thus the sequence of failure.

ASCE Method: This method also indirectly controls the line reliability by controlling the individual component reliabilities. This is done by means of two factors: factor (G) to adjust the global reliability of the line and factor (C) to adjust the component reliability. The factor C is also used to control the preferred sequence of component failure.

It should be noted that the ASCE method is based on component reliability whereas the IEC method is concerned with the line reliability.

6.3 Design Equations

IEC Method: The design equation in the LRFD format is given by:

$$\phi R_n > \gamma_u E [DL+Q_{RP}]$$

where

γ_u = reduction(or use) factor dependent on span dispersion

E[ ] = Effect of

Q_{RP} = Extreme loading event at a point corresponding to return period RP (RP can vary between 50 to 500 years)

R_n = Nominal strength of component

DL = Dead Load

ϕ = $\phi_S \phi_Q \phi_C \phi_N$

and

ϕ_N = Factor related to the number of components under critical load

ϕ_Q = Factor related to the quality of the component during fabrication and construction

ϕ_C = Factor related to the relationship between the actual exclusion limit, R_c, and the assumed value of 10% exclusion limit of structural component,

ϕ_S = Factor related to the strength coordination between components.

6-V Method: The LRFD equation is given by:

$$\phi_{\beta,V} R_m > E [\gamma_{\beta,V} Q_m]$$

where

Q_m = The mean value of load

R_m = The mean value of strength,

$\phi_{\beta,V}$ = Resistance factor = $\exp(-\alpha_R \beta V_R)$

$\gamma_{\beta,V}$ = Load effect factor = $\exp(\alpha_Q \beta V_Q)$

β = The reliability index

V_R = The COV of resistance

V_Q = The COV of load

α_R, α_Q = Factors obtained through reliability studies.

ASCE Method: The design equation for this method is given by:

$$\phi R_n > E [\gamma_D DL + Q_{RP}]$$

where

$E[\ ]$	=	Effect of
Q_{RP}	=	Extreme loading event at a point corresponding to return period RP
R_n	=	Nominal strength of component
DL	=	Dead Load
ϕ	=	A strength factor containing variables associated with resistance and can be modified to be used for strength coordination
γ	=	A load modification factor
γ_D	=	Dead load modification factor

6.4 Climatic Loads

IEC Method: The wind load is calculated from the maximum annual wind speed at average minimum daily temperature or a reduced wind at 50 year return period minimum temperature.

The ice load and wind-on-ice load are calculated from available data on ice storms. The ice load is calculated without considering the wind that prevailed during ice storms. However the calculation of wind-on-ice load takes into consideration the wind speed during ice storms. The wind-on-ice will be a function of four parameters: ice thickness, ice density, conductor shape and wind speed. As it is very unlikely that all these parameters contribute to maximize the wind-on-ice load, a total of four cases are considered. This is done by associating one parameter with a low probability and combined with the remaining three at a high probability. This procedure is very cumbersome and should be simplified considerably.

β-V Method: The wind load is calculated from the annual extreme wind speed measured at a single location in the vicinity of the transmission line.

The ice load and wind-on-ice load are calculated from any available source such as national ice maps and loading guides. The ice load is calculated without taking into consideration the effect of wind existed during ice storms. The wind-on-ice load is calculated by combining the extreme ice thickness with the maximum wind speed that prevailed during the ice residency period.

Even though the procedure may be simple to use, the validity of this approximate method should be verified before it is finally accepted.

ASCE Method: The procedures used to calculate wind, ice and wind-on-ice loads are very similar to the ones used in the β-V method.

6.5 Target Reliability

IEC Method: The design reliability for the line is chosen from three given levels which corresponds to 50, 150 and 500 year return periods. This method of choosing target reliability does not provide a continuity with the existing designs.

β-V Method: The design reliability for the line components is chosen by calibration of existing designs to provide a continuity. Modifications to this reliability level could be achieved by approximate correction factors.

ASCE Method: In this method, the target reliability is used only in a relative sense. A reference component reliability, which is indicative of the many components of the system that are currently performing satisfactorily, is chosen. The line reliability is controlled by global reliability factors.

The procedures used in the ASCE and β-V methods to choose target reliability are more realistic and practical than the one used in the IEC method.

6.6 Other Aspects

IEC, β-V and ASCE Methods: The construction, maintenance and security loads are also considered in these methods.

The effect of different span lengths (Use Factor) is considered only in the IEC method, not in the β-V and ASCE methods. The use of "Use Factor", which accounts for the effect of different span lengths, needs to be further studied.

6.7 Summary and Conclusions

Some of the key parameters of the three RBD methods are summarized below.

Basic Concepts: The IEC method directly controls the reliability of the entire line by treating it as a system while the β-V and ASCE methods indirectly control the line reliability through the component reliability. Treating the line as a system is probably the most effective way to design. However the approximations used in the other two methods may simplify the design calculations.

Component as defined in IEC methods is a tower, foundation, etc., while it represents a member in the ASCE method. The IEC method does not discuss the design of a member.

Climatic Loads: All the three methods use different techniques to calculate wind, ice and wind-on-ice loads. It is difficult to assess the relative merits of these methods unless these are applied to typical situations and hence further study will be useful.

In general, the procedures recommended by all the three methods to calculate ice and wind-on-ice loads need simplification, improvement and verification. Moreover, the lack of availability of required weather data may be a serious obstacle in effectively applying RBD methods to transmission lines.

Target Reliability The target reliability in IEC method is given in absolute terms, while in the β-V and ASCE methods it is given in relative terms. Even though the absolute target reliability, which may not be attainable due to the uncertainities in the disign parameters, may be useful it is very important to know the relative reliability of the new design compared with the existing designs. It should be noted that the assessment of absolute reliability is extremely difficult and may lead to erroneous results.

Effect of Different Span Lengths: The IEC method considers the effect of different span lengths (by means of a Use Factor) in assessing line reliability while the other two methods do not. If properly done, the application of Use Factor may result in a realistic assessment of line reliability. However, more work is required before any final acceptance.

In summary the following remarks could be made about the RBD methods reviewed in this report:

- The IEC method directly calculates the line reliability while the other two methods do it only indirectly.
- The IEC method claims to give the reliability in absolute terms while the other two methods provide reliability related to existing designs.
- The application of Use Factor, recommended in the IEC method, should be studied further before any final acceptance.
- It would be useful to compare the results of these methods if the procedures to calculate climatic loads are made more uniform.
- More work should be carried out to develop improved data bases for weather related loads, tower component strength, etc.

It would be useful for Ontario Hydro to develop its own RBD method by incorporating the beneficial features of the methods discussed above and including other items that are unique to the Corporation's current design practices. A brief outline of such a method is discussed in the next section.

7.0 PROPOSED RELIABILITY-BASED DESIGN METHOD FOR ONTARIO HYDRO

7.1 Introduction

The efforts to promote the ASCE and IEC design methods for transmission structures have led to the formation of two schools of thoughts. One school of thought claims that the implementation of the RBD methods would result in economically efficient designs. But the other school argues that it may be

difficult to accurately determine line reliability because of the considerable line length to deal with and lack of sufficient design data. Because of the differences among transmission line designers, none of the proposed RBD methods have yet been adopted as a design code.

Recently the IEEE has established a Task Force/6/ to evaluate the IEC and ASCE reliability-based design methods and to assess the feasibility of developing a new design format that would be more readily accepted by the transmission line designers. In this section an outline of a RBD design method, which will combine the desirable features of the ASCE and IEC methods, is described.

7.2 Scope of the Proposed RBD Method

The scope of the proposed method may be divided into three main areas:

1. Based on the review done in the previous sections on the two main RBD methods, prepare a list of all relevant parameters that would be useful for developing the new RBD method. (This has been already completed.)

   These parameters would equally benefit the existing design methods.

2. Study the relationship between the safety provisions (to be adopted in the new method) and social, economic and legal interests. This study is important to establish the constraints which would influence the levels of reliability for use with different line securities.

3. Develop statistical and other necessary modern tools to assess the following:

   a. Reliability levels of existing lines by calibration.

   b. More accurate behaviour of line components such as foundation, tower and hardware.

   c. Reliabilities of lines or line segments and partial safety factors.

   d. Transfer of meteorological data from the weather stations to the line route.

   e. Weather related loads on transmission lines accounting for the directional characteristics of wind, terrain effect, etc.

   f. Drag coefficients for single and bundle conductors.

   g. Strength of line components such as foundations and towers.

   h. Other relevant parameters unique to Ontario.

Note: A significant amount of work has already been done in Ontario Hydro to obtain the parameters listed in a), d), e), f) and g).

7.3 Format of the Proposed RBD Method

The following is the general form of the proposed design method:

$$\phi_i R_e > E [\gamma_j Q_{RP}]$$

where

$E[\ ]$ = Effect of

Q_{RP} = Extreme loading event corresponding to the return period RP

R_e = Strength of component at exclusion limit of e

$\phi_i = \prod_{k=1}^{n} \phi_k$ = Partial strength factors containing variables associated with resistance

$\gamma_j = \prod_{l=1}^{m} \gamma_l$ = Partial load factors containing variables associated with loads

Although essentially simple in concept, the above partial factor approach would require the use of different factors for each component type, size, type of loading and usage.

In the following sections, procedures for determining the loads and resistance factors will be briefly discussed.

7.3.1 *Method for Determining Safety Factors*

It is proposed that the partial load and strength factors, "γ" and "ϕ", be based on reliability theory using the advanced first-order-second-moment (AFOSM) method. This method is well established and could be easily applied to calculate these factors provided appropriate data is available.

7.3.2 *Method for Assessment of Weather Related Loads*

As indicated earlier, considerable amount of work has been done in Ontario Hydro to establish data base for wind, ice, and wind-on-ice loads /5,11/ on a probabilistic basis for the province of Ontario.

The following are the key parameters required for calculating the weather related loads:

- *Annual extreme mean wind speeds*: These could be readily obtained from AES weather data base and Ontario Hydro's in-house data base.

- *Data on ice and wind-on-ice*: Data base has been already established for about 30 weather stations in Ontario/11/.

- *Data on wind direction corresponding to extreme wind speeds*: A procedure has been developed in Ontario Hydro/12/ to calculate wind loads on transmission lines taking into account the effect of wind direction.

- *Appropriate conductor drag coefficients and span factors*: These factors are necessary to account for the conductor shape and terrain effect. The wind and ice load monitoring project in Ontario Hydro/13/, which has been operational since 1975, has provided a fair amount of information on these factors. Work is continuing to gather more information.

- *Methods for transferring weather data from the weather stations to the line route*: Methods for the data transfer are still in the developmental stage and are expected to be completed in about 2 years. Until then approximate methods based on professional judgment and experience should be used.

7.3.3 *Method for Determining Component Strength*

There is currently information available in the literature that could be used to determine the characteristic strength of transmission line components. However, since more information is needed to improve the reliability, leading utilities in North America, including Ontario Hydro, are conducting further studies in this area.

7.4 Calibration of Current Designs

The reliability of the lines designed by the proposed method should be comparable to that of the similar existing lines in order to maintain the traditionally acceptable levels of reliability.

At present there is not sufficient reliable information on performance and failure of transmission lines to establish reliability levels for developing RBD methods. In the absence of this statistical data, recourse must be made to "calibration" of the proposed method against our current design practice which has been in use for several decades.

In this context, "calibration" consists of ensuring that, on average, lines designed according to the proposed method would have reliability equal to that of similar lines designed according to the existing code.

A method developed in Japan for relating safety factors to reliability/14/ will be used for calibration. Basid on this method a compiler program "CALIBER" has been developed to determine the inherent reliabilities of existing transmission lines. This information would be important in the selection of target reliabilities of new lines.

7.5 Target Reliability

Acceptable levels of risk of attaining a limit state, to be used as targets in design, must be assessed with due regard to social and economic criteria applicable to the line under consideration. These criteria vary with the level of line security and the prevailing social and economic climate in the area in which the line is to be built.

Since a transmission line may be hundreds of kilometers long, it would be unrealistic and uneconomical to set a single target reliability for the entire line (eg., part of the line going through heavily populated areas should, in general, have higher reliability than that going through sparsely populated farm land).

In this study it is proposed that the concept of segment target reliability be adopted. According to this concept the line will be conveniently divided into segments, each segment consisting of towers with approximately the same ruling span. Some of the parameters to be considered in determining the segment target reliability are:

(a) Line security level
(b) Location of line (number of people at risk, legal consequences, etc.)
(c) Line accessibility (restoration time if failure occurs).

7.6 Summary

An outline of the proposed Reliability Based Design method is presented along with discussion on several important parameters. A flow chart giving the details of the parameters affecting reliability and the proposed method is shown in Figure 9.

The key difference between the new approach and the other methods reviewed in this report is the way the target reliability is calculated. The use of "segment target reliability" instead of a single reliability for the whole line would lead to a better control on line security and eventual economic benefits.

The other important new features of this proposed method, that are not effectively considered by the current methods, are:

1) use of measured conductor drag coefficients,
2) accounting the effect of wind direction on wind load, and
3) use of data that are transferred from weather stations to line route.

It is believed that the proposed approach, along with Ontario Hydro's data base on loads and field measurements, would provide a consistent and reliable design tool for transmission structures. At the same time the reliability of the new designs would be comparable to the reliability of the current designs.

It should be noted that the improved methods to determine wind loads could be useful in current design methods as well.

7.7 Further Work

Further work will be done to develop the full details of the proposed method. Plans are already in place for obtaining some of the new information required to apply the proposed method.

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APPENDICES A, B AND C

DETAILED DESCRIPTION OF RELIABILITY-BASED DESIGN METHODS

In the following appendices, the steps required to apply the β-V, ASCE and IEC reliability-based design methods will be described in some detail. The review and general discussion are given in the main text of the report.

APPENDIX A

RELIABILITY-BASED DESIGN METHOD PROPOSED BY IEC

INTRODUCTION

In this Appendix, the several steps that are required to apply the IEC reliability-based method will be described in some detail. The discussion will be limited to the general application of the method and for any detailed use of the method the procedures and information given in /2/ should be followed. As pointed out earlier (Section 3.0), not all the parameters considered in the reliability calculations should be statistically treated. It depends upon the degree of variability of a particular parameter. As will be seen later the design method proposed by IEC does treat some of the parameters deterministically.

DESIGN EQUATION

The equation for the reliability-based design of transmission lines, in the general LRFD format, is given below.

$$\phi R_n > \gamma_n E[DL+Q_{RP}] \qquad \text{(A1)}$$

where

γ_n	=	Reduction (or use) factor dependent on span dispersion
E[ ]	=	Effect of
Q_{RP}	=	Extreme loading event at a point corresponding to return period RP (RP between 50 to 500 years)
R_n	=	Nominal strength of component
DL	=	Dead Load
ϕ	=	$\phi_S \phi_Q \phi_C \phi_N$

where

ϕ_N	=	Factor related to the number of components under critical load
ϕ_Q	=	Factor related to the quality of the component during fabrication and construction
ϕ_C	=	Factor related to the relationship between the actual exclusion limit, R_e , and the assumed value of 10% exclusion limit of structural component,
ϕ_S	=	Factor related to the strength coordination between components.

The right side of the equation represents the load applied to the line and the left side represents the strength of the line. The balancing of the design equation by choosing appropriate factors is expected to result in a system with the desired reliability.

APPLICATION OF THE METHOD

The following are the necessary steps to apply the above reliability-based design equation for transmission lines.

Step 1: Select Required Reliability Level

The reliability level of a transmission line system is selected according to the voltage of the line and the importance of the line in the overall transmission line network. Three reliability levels are considered:

(1) Corresponds to a 50 year return period, the minimum design requirement.
(2) Corresponds to a 150 year return period and is used for lines greater than 230 kV or for important lines less than 230 kV.
(3) Corresponds to a 500 year return period and is used for designing lines carrying greater than 230 kV.

Step 2: Calculate Climatic Variables

In this step design wind speed and ice accretion required to calculate wind,ice and wind-on-ice loads are chosen as explained below.

(a) Wind Speed

The wind speed used for calculating design wind loads is determined from the mean and standard deviation of measured annual extreme wind speed values and the desired reliability level associated with the transmission line. It is generally recommended that about 30 years of data from weather stations in the proximity of line be used in the load calculations. The IEC method uses 10 minute average wind speed obtained at a height of 10 meters above the ground. If the available wind data is in different format then it should be converted to the IEC format by means of established empirical relationships. The effect of terrain roughness (along the transmission line route) on wind should also be considered in design calculations.

(b) Ice Accretion

Depending upon the location of the line, information on ice accretion could be obtained by one of the following three methods.

(1) About 20 years of meteorological data from nearby weather stations, in conjunction with icing models, could be used for calculating mean and standard deviation of extreme annual ice thickness. If possible the reliability of the icing model should be verified by using about 5 years of ice data gathered on a nearby transmission line.

(2) Maximum ice load, determined from measurements done over a period of at least 5 years at nearby monitoring stations, could be used for calculating the mean and standard deviation of annual extreme ice.

(3) Historical ice load data, if any available, from nearby monitoring stations could also be used to calculate the mean and standard deviation of maximum ice load.

Step 3: Calculate Climatic Loads

In this step the information on wind and ice described in Step 2 is used to calculate the wind, ice and wind-on-ice loads on various transmission line components.

(a) Wind Load

Wind loads on transmission line components are calculated using the following information:

- Design wind speed chosen in step 2
- Shape and dimensions of the components
- Gust response factor

If available, information on direction associated with extreme winds should also be taken into consideration.

(b) Ice load

Ice loads on transmission line components are calculated using the following information:

- Mean and standard deviation of ice data (Step 2.)
- The desired reliability level of the transmission line.
- Conductor size and its height above ground.
- Degree of uniformity of ice accretion on the component (to account for unbalanced loads).

(c) Wind-on-Ice Load

The maximum load due to the combined effects of wind and ice on a component is a function of ice accretion, ice shape and wind speed. As it is highly unlikely that all these three parameters contribute concurrently to maximize the load, it is more logical to treat these variables independently and combine low probability value of one variable with high probability values of the other two.

Step 4: Calculate Loads Required for Failure Containment

This is usually done using deterministic methods and is not a part of the IEC report.

Step 5: Calculate Loads Required for Safety

Usually National Regulations and/or Codes of Practice set minimum safety standards. In the IEC document, a number of additional requirements are listed. Since the safety standards are also set using deterministic methods, they are not expanded in the IEC report.

Step 6: Determine Required Strength Coordination

The strength of various components of a system are coordinated to assure a preferred sequence of failure, i.e., a component whose failure is supposed to cause the least amount of damage to the system is the first to fail in case of excessive loads. The following criteria are suggested for appropriate strength coordination:

(1) Failure of a component should cause minimum secondary effect to the rest of the system.

(2) The time and cost of repair should be kept to a minimum.

(3) The failure limit of the component that was chosen to fail first must be equal to its damage limit. This is to ensure that the component actually fails and does not remain in service in a damaged state.

(4) Low cost components in series with high cost components should be at least as reliable as the latter unless purposely designed otherwise (e.g. mechanical fuse).

Considering all the possible failure sequences in a transmission line system, the IEC document proposes a system in which tangent tower is the first component to fail.

Strength coordination is achieved through one of the following methods:

(1) For the first component use the calculated design loads together with strength at 10% exclusion limit. For the rest of the components use the same design load but a higher strength.

(2) For different components, choose strength factors such that strength coordination is achieved with a high degree of reliability, e.g., design component No. 2 so that there is a 90% probability that it fails after component No. 1 has failed.

The IEC document recommends the second method because it provides some control over the probability of achieving the desired strength coordination.

Step 7: Select Appropriate Correction Factors

(a) *Factor Related to Span Dispersion (γ_s)*

Field variables such as terrain type may require that the actual span of some towers to be less than the design span. In many cases this would make the design of the transmission tower more conservative than that intended by the designer. The ratio of the actual span length to the design span length is the "USE FACTOR". This factor, which usually varies between 0.4 and 1.0, is a function of terrain type, the number of different types of tower available for spotting and the constraints on tower locations. The IEC document provides values for the mean and standard deviations of the use factor as a function of tangent tower types and the terrain type. It also provides a method of calculating the reduction factor which accounts for the use factor variation in the design equation.

(b) *Strength Factors Related to Coordination (ϕ_s)*

These factors are obtained using one of the methods described in Step 6.

(c) *Strength Factor Related to the Number of Components Subject to Critical Loading (ϕ_N)*

A transmission line system contains a number of components that are placed in series with each other. Insulator skirts in an insulator string or a stretch of tangent towers are typical examples. The reliability of such a system depends on the number of components which experience the limit loads. The larger this number is, the greater is the probability of failure. The strength distribution of a system consisting of a number of components can be calculated from the strength distribution of each component (using a Monte Carlo simulation method, for example). The strength factor, ϕ_N, is introduced to account for the decrease in the reliability of the system when more than one component is subjected to the same loading condition. This factor is defined as the ratio of the 10% exclusion limit of strength when N components are used to the 10% exclusion limit when 1 component is used. Value for ϕ_N for N=2, 5, 10, 20, 50 and 100 are given in the IEC report.

Step 8: Select Characteristic Strengths for the Components

In many calculations the value of the 10% exclusion limit of strength (of a component) is used as the characteristic or nominal strength. It is however known that for many materials the characteristic strength is likely to be better than the 10% exclusion limit. If for a particular material, there is enough evidences to support this, then the 10% exclusion value required for the design equation could be calculated by multiplying the characteristic strength by the strength factor, ϕ_c. The factor ϕ_c is obtained from the relationship:

$$\phi_c = (1-1.28\ V_r)/(1-K_c V_r)$$

where V_r is the COV of the component strength and K_c is a coefficient depending on the type of material, the fabrication practice and the type of distribution function of the resistance.

Step 9: Design Components Based on the above Loads and Strengths

Using the design equation (A1) and the loads, strengths and factors obtained in the above steps, the transmission line system can be designed (or checked) for the desired reliability.

APPENDIX B

RELIABILITY-BASED DEIGN METHOD USING β-V METHOD

INTRODUCTION

In this section the major steps required for applying the β-V method are described in some detail. Reference /1/ provides a more detailed description of these steps and contains tables and charts to help in choosing the required design parameters.

DESIGN EQUATION

The LRFD equation for the β-V method is written as:

$$\phi_{\beta,V} R_m > E [\gamma_{\beta,V} Q_m] \qquad \text{(B1)}$$

where

Q_m = The mean value of load

R_m = The mean value of strength,

$\phi_{\beta,V}$ = Resistance factor = $\exp(-\alpha_R \beta V_R)$

$\gamma_{\beta,V}$ = Load effect factor = $\exp(\alpha_Q \beta V_Q)$

β = The reliability index

V_R = The COV of resistance

V_Q = The COV of load

α_R, α_Q = factors obtained through reliability studies.

APPLICATION OF THE METHOD

The following are the necessary steps to apply the above reliability-based design equation (B1) for transmission lines.

Step 1: Calculate Dead Loads

The following dead loads are considered in the design:

(1) Weight per foot of each conductor and shield wire. (The effect of sag on length is usually neglected.)
(2) Weights and locations of centres of gravity of other attachments.
(3) Self weight of structure.

Step 2: Calculate Climatic Loads

(a) Wind Load

The following steps are suggested to calculate wind loads:

- Use mean yearly fastest mile wind speed (corresponding to 10 meters above ground level). Fastest mile wind speed is defined as the fastest average speed of one mile of air passing an anemometer. Use data from nearby stations.
  If the fastest mile wind speed data is not available then convert the data by appropriate means.

- Determine the COV of the above data. If records are available for only a short period of time (less than 10 years), necessary corrections should be applied.

- Adjust COV to account for the distance between anemometer site and line site. This can be accomplished by using

$$V_W = (V^2_M + V^2_U)^{1/2}$$

  where V_M is the COV of the measured data and V_U is an estimate of the uncertainty related to site location and local topographical conditions. When V_U is not known, use V_U=0 and modify design spans or design wind speeds on a judgmental basis for unusual local conditions.

- Determine wind speed at the component level.

- Choose appropriate force (drag) factors for the component.

- If needed, adjust air density for local temperature and elevation above sea. The standard temperature at sea level is usually used.

- Select a span factor. A value of unity is commonly used; however, if a more realistic value is available from a reliable source it should be used.

- Consider dynamic effect of wind by applying a suitable gust factor.

- If necessary consider special terrain features for each structure in a line which is placed in areas of unusual topography. This type of calculations require a detailed study of the area under consideration.

(b) Ice Load

Use mean and COV of yearly ice thickness obtained from:

- Mean value from NESC and estimated COV.
- ASCE loading guide (use a high of 0.4 for COV).
- Data from local measurement.

Assume a unit weight of ice typically 54 lb/ft^3. Also consider the effects of local terrain on ice accretion.

(c) Wind-on-Ice Load

- Determine the duration that maximum yearly ice is resident(a default value of 3 to 7 days is typically used).

- Compute maximum wind that will act during ice residency. For a seven-day residency, the weekly wind mean & COV are estimated from:

$$M_w = M_y - 3.082\ S_y$$
$$S_w = S_y$$
$$V_w = M_w/S_w$$

where M = mean, S = standard deviation, V = coefficient of variation, w = weekly and y = yearly.

Step 3: Determine Resistance Parameters and Resistance Checking Procedure

Determine the statistical parameters such as mean and variance for strength data. Also choose appropriate limit states and resistance checking equations for the system.

Step 4: Select Yearly Target β for Design

The appropriate β for the system being considered can be obtained from:

1. Individual utility calibration: A utility can compute β values for existing lines and use them as basis for new lines.

2. NESC or other national codes should provide a table of β values to use in various situations (e.g. at crossings, for lifeline structures, etc.). Since at present it is not the case, the district loadings given in the code can be used.

3. The default value of 3 based on a calibration study by the American Institute of Steel Construction. (Note: The same study indicated that the one year risk that the utilities are willing to accept is equal to the 50-year risk acceptable to the building industry.)

Step 5: Determine Factored Loads

The following factors are used in conjunction with parameters obtained in Steps 1 & 2 to provide the factored loads.

1. *Dead load:* A universal dead load factor of 1.2 can be used. (The manufacturer-listed weights can be taken as means.)

2. *Wind load:* Use the mean yearly maximum velocity and compute the wind velocity factor as: $\gamma_w = \exp(+0.75\ \beta\ V_w)$ where V_w is the COV of the yearly maximum wind. The factored wind velocity is then $\gamma_w\ M_w$ where M_w is the yearly mean wind.

3. *Ice load:* Use the mean yearly maximum ice thickness and compute the load factor as:

$$\gamma_I = \exp(+0.30\ \beta\ V_I)$$

where V_I is the COV of the yearly maximum ice. The factored ice thickness is then $\gamma\ M_{IY}$ where M_{IY} is the yearly mean ice thickness.

4. *Wind-on-Ice load:*

- Compute the mean and load factor as in step 3
- Reduce mean yearly maximum velocity and COV to weekly values using the method given in Step 2. Then the load factor is

$$\gamma_{WW} = \exp(+0.75\ \beta\ V_{WW})$$

where the WW subscript refers to weekly wind (or assumed length of ice residence if other than one week). The factored wind velocity assumed to act on the iced conductors is γ_{WW} M_{WW} where M_{WW} is the mean weekly wind.

Step 6: Structural Analysis to Calculate Load Effect:

Perform a structural analysis and express the results in a form easily usable in the resistance checking procedure.

Step 7: Checking Resistance

It should be made sure that the factored resistance is always greater than the factored loads for each component and for each load combination considered.

The factored resistance is given by $\phi_c\ \phi\ R_m$, where,

R_m = Mean resistance (e.g., the mean pole MOR),

ϕ = Capacity reduction factor given by: $\phi = \exp(-0.75\ \beta\ V_R)$,

V_R = COV of the resistance, and

ϕ_c = Factor used to establish a preferred sequence of failure.

The structural analysis and the resistance checking procedure may be carried out by an accepted computer program.

APPENDIX C

MODIFIED BASE LINE (ASCE) METHOD

In this Appendix the steps required to apply the Modified Base Line (ASCE) Method or C.G. method will be discussed in some detail. More detailed information on applying the method to design transmission lines are available in /3/. Hereafter the Modified Base Line Method will be referred to as ASCE Method.

DESIGN EQUATION

The basic design equations of the ASCE method are:

$$\phi R_n >= E\,[\gamma_D DL + \gamma_W Q_{50\text{-}W}]$$
$$\phi R_n >= E\,[\gamma_D DL + \gamma_I Q_{50\text{-}IL} + \gamma_W Q_{50\text{-}WIr}]$$
$$\phi R_n >= E\,[\gamma_D DL + (AL \text{ or } CL)] \qquad \text{(C1)}$$

where,

R_n = the nominal resistance of the component based upon the lower five percent exclusion limit.

γ_D = the load factor applied to dead loads, recommended as 1.2.

DL = dead load

γ_W = load factor applied to wind load, modifies the reliability of entire structure.

$Q_{50\text{-}W}$ = loads produced by fastest mile wind velocity with a 50-year return period. The wind direction is taken to produce the largest load effect.

γ_I = load factor applied to ice load.

$Q_{50\text{-}IL}$ = ice load produced by ice thickness corresponding to a 50-year return period.

$Q_{50\text{-}WIr}$ = loads produced by reduced wind velocity, V_r , blowing on conductors and components coated with 50-year ice.

AL = assumed accidental events.

CL = loads produced by construction/maintenance loads.

The reliability of the entire structure (global reliability) can be increased by the global reliability adjustment factor, G, which leads to γ values greater than one. The component reliabilities can be increased through the component reliability adjustment factor C by using ϕ values less than unity, or they can be decreased by using ϕ values greater than unity.

APPLICATION OF THE METHOD

The following steps are needed to apply the ASCE method to transmission line design.

Step 1: Calculate Dead Loads

The following dead loads are considered in the design

- Weight per foot of each conductor and shield wire.
- Weights and location of centres of gravity of other attachments.
- Self weight of structure, typically by defining unit weights of materials.

Step 2: Calculate Climatic Loads

(a) Wind Load:

- Use mean yearly fastest mile wind speed corrected to 10 meters (33 feet) above ground level. About 20 years of mean yearly fastest wind speed is considered sufficient. If the available wind data is not in the fastest mile format then it should be modified appropriately.

- Adjust COV to account for the distance between anemometer site and line site. This can be accomplished by using

$$V_W = (V^2_M + V^2_U)^{1/2}$$

where V_M is the COV of the measured data and V_U is an estimate of the uncertainty related to site location and local topographical conditions. When V_U is not known, use V_U=0 and modify design spans or design wind speeds on a judgmental basis for unusual local conditions.

- Determine wind speed at the component level.

- Obtain the 50-year return wind velocity, V_{50}. This can be found by plotting historical wind data on Gumbel type I probability paper. Alternately, use:

$$V_{50} = V_{avg} (1 + 2.59\ COV_W)$$

where V_{avg} is the average of the annual maximum wind data.

- Choose appropriate force (drag) factors for conductors and structural components.

- Adjust for elevation above sea level and design temperature. The density at sea level and standard temperature is usually used, consistent with the assumptions made in calibration.

- Select a span factor. A value of unity is commonly used; however, if a more realistic value is available from a reliable source it should be used.

- Consider dynamic behaviour by using a suitable gust factor.

- Consider special terrain features. This must be done for each structure in a line.

(b) Ice Load:

The following two steps are required to collect appropriate information on ice accretion:

- Collect statistically adequate mean yearly ice thickness on circular conductors from one of the following sources:

  - NESC district values.
  - ASCE loading guide values
  - results of a local study of historic storms data.

- Plot the ice thickness data, from historic ice storms, on Gumbel Type I probability paper and find the 50-year return period value. The ASCE report already gives 50-year values. Alternatively, the NESC mean values, I_{avg}, can be used with an assumed COV and the following relationship

$$I_{50} = I_{avg} (1 + 2.59\ COV_I)$$

  to give a 50-year value. It is not known if NESC district values are intended to be yearly or lifetime maximum values; comparison with the ASCE loading guide values indicates they are more appropriate as annual values.

(c) Wind-on-Ice Load:

- Determine the length of time maximum ice is resident. Three to seven days is a typical default value.

- Compute maximum wind speed that will act during ice residency, V_r. The recommended values are:

  - with 50-year glaze ice, use $W_r = 0.4\ W_{50}$,
  - with 50-year wet snow, use $W_r = 0.3\ W_{50}$.

These correspond to an ice residency of one-half week. The unit weight of glaze ice is usually taken as 54 lb/ft^3.

Step 3: Resistance Checking Procedure

Choose appropriate limit states and resistance checking equations for the system to be designed. Also determine lower five percent exclusion limits.

Step 4: Selection of G Values

The G values are used to modify the global reliability of the entire structure and are listed in Table C-1.

Table C.1

Global Reliability Factor, G, and Load Factors

G=1	2	3	4	6	9	13	19	28	40	56	80	110
γ_w=1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2

γ_l=1.2 γ_w

(For example, to double the reliability of a given structure, use γ_w = 1.1 and γ_l = 1.32).

Step 5: Factored Loads

These are computed as indicated in Eq. C1.

Step 6: Structural Analysis

This is done using an accepted computer program.

Step 7: Resistance Checking

The objective of this step is to show that the factored resistance is greater than the effects of the factored loads for each component under each load combination considered. The factored resistance is ϕR_n where ϕ is a factor chosen to control sequence of failure. It is obtained from Table C.2 as a function of the component reliability value, C. In this table e is the exclusion limit, e.g. an e value of five corresponds to a lower five percent exclusion limit and V_R is the COV of the resistance.

Table C.2

Strength Factor ϕ to Adjust Component Reliability by Factor C

C =	10			2			1			1/3		
V_R =	0.10	0.15	0.20	0.10	0.15	0.20	0.10	0.15	0.20	0.10	0.15	0.20
e = 1	0.89	0.89	0.91	0.96	1.04	1.16	1.03	1.16	1.30	1.22	1.39	1.57
5	0.82	0.77	0.72	0.88	0.90	0.92	0.94	1.00	1.03	1.12	1.20	1.25
10	0.78	0.72	0.65	0.84	0.84	0.83	0.90	0.93	0.93	1.08	1.12	1.13
15	0.76	0.69	0.61	0.82	0.80	0.78	0.88	0.89	0.88	1.05	1.07	1.06
20	0.75	0.67	0.58	0.80	0.78	0.74	0.86	0.86	0.83	1.02	1.03	1.01
50	0.68	0.58	0.48	0.73	0.68	0.62	0.79	0.79	0.69	0.94	0.90	0.84

Thus to increase the reliability of a component with C = 10, V_R =.10 and e = 5 percent, use ϕ = 0.82. Note the base line values are C = 1, V_R =. 15 , e = 5 percent and ϕ = 1.00.

The resistance of each member should be checked using the appropriate checking equation and its size changed if necessary. Changes in component size may necessitate a reanalysis followed by another check.

Appendix D

PROBABILITY OF FAILURE

The ordinary meaning of failure is qualitative; it implies that the system becomes unfit to accomplish a specific operation. Reliability theory which is totally based on the concept of failure has been developed from quantitative point of view where failure is defined as the event which occurs when a system performance transgresses its tolerance limits. This lends the notion of failure somewhat artificial flavour. The artificiality of the reliability model is common to all mathematical models, because they are based on a quantitative definitions of a qualitative concept. In this report, the qualitative meaning of failure as "unfit for use" is replaced by the quantitative meaning of failure as "tolerance limits transgression".

BASIC DEFINITIONS

Consider the failure condition

$$R\ (x_i,\ i=1,n) \leq Q\ (y_j,\ j=1,m)$$

where R and Q are the strength and load respectively. R and Q are functions of several random design factors x_i and y_j.

Define the limit state function, failure function or performance function as :

$$g(U_k) = R(x_i) - Q(y_j)$$

where the design factors are $U_k = (x_i - y_j)$.

g(U) is defined so that the failure condition is

$$g(U_k) \leq 0$$

Define the failure surface or the limit state as,

$$g(U_k) = 0$$

The failure surface is the boundary between the safe and failed regions in the design parameter space. In general there can be several limit states for a component, e.g., yield, buckling, fatigue, ..etc.

THE FULL DISTRIBUTIONAL APPROACH

It is assumed that the exact statistical distribution of each design factor U_i is known.

The probability of failure p_f is defined as the probability of the failure event,

$$p_f = p(g(U) \leq 0)$$

for example if R and Q are the basic variables, the probability of failure is

$$p_f = p([R-Q] \leq 0) = p(R \leq Q)$$

In general, p_f can be computed as

$$p_f = \int_{\Omega} f_U(u_1,.....,u_n)\, du_1....du_n$$

where Ω is the region of U where $g(U) \leq 0$, f_U is the joint pdf of U, and n is the number of design factors. f_U is a surface in (n+1) dimensions space. The volume under the joint pdf f_U is one.

SPECIAL CASES

A. Only one Random Variable

Since the number of random variable is 1, then the joint pdf is a surface in 2 dimensions space (n=1), i.e. the joint pdf is a curve as shown in Figs. 10(a) and 10(b).

If $Q=Q_0$, a deterministic real number, then the probability of failure is

$$p_f = p(R \leq Q_0) = F_R(Q_0)$$

which is the shaded area under the curve of Fig.10(a).

Similarly, if $r=R_0$, a deterministic real number, then the probability of failure is

$$p_f = p(R_0 \leq S) = 1 - F_Q(R_0)$$

which is the shaded area under the curve of Fig. 10(b).

B. Two Random Variables : the Basic Load-Strength Interference Problem

In general, for design factors R and Q, the probability of failure is,

$$p_f = \int_{\Omega} f_{RQ}(r,q)\, dr\, dq$$

where f_{RQ} is the joint pdf of R and Q, which is a surface in 3 dimensions space (n=2) as shown in Fig.11/15/. The volume under this surface in the failure region Ω is the probability of failure. The interference problem for this special case (2 random variables) and also be presented as shown in Fig.12.

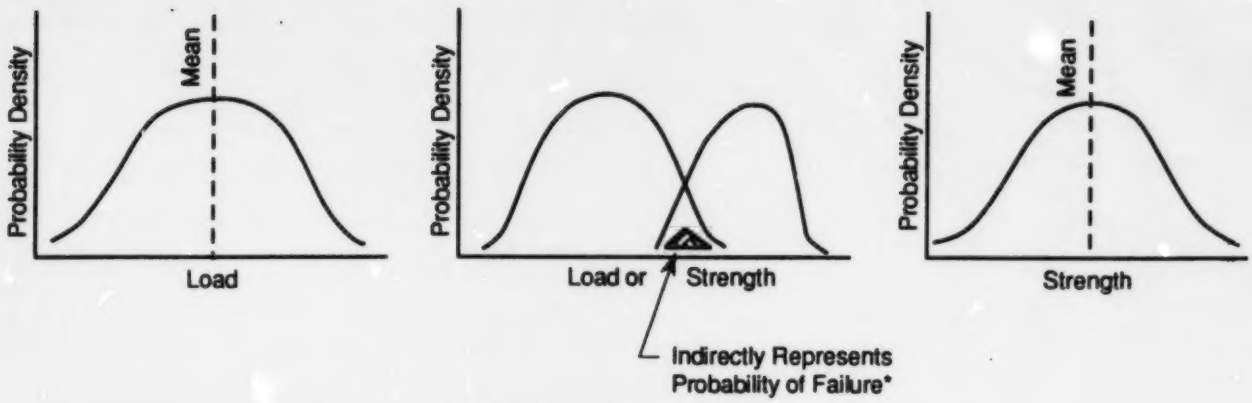
Now, assuming that R and Q are independent random variables, then

$$p_f = \int_{\Omega} f_R(r)\, f_Q(q)\, dr\, dq = \int_0^{\infty} f_Q(q)\, dq \int_0^{q} f_R(r)\, dr$$

$$p_f = \int_0^{\infty} f_Q(q)\, F_R(q)\, dq$$

Similarly, it can be shown that,

$$p_f = 1 - \int_0^{\infty} f_R(r)\, F_Q(r)\, dr$$



* Obtained by Combining 'Load' and 'Strength' Distributions at Random

FIGURE 1

BASICS OF PROBABILITY METHODS

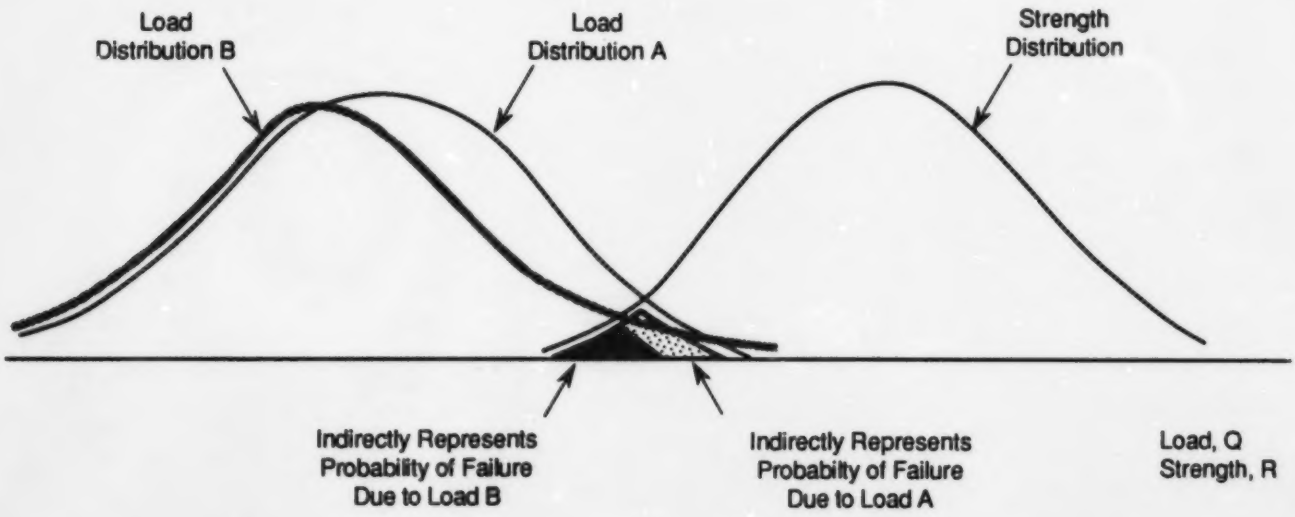


FIGURE 2

EFFECTS OF CHANGE IN LOAD DISTRIBUTION SHAPE ON PROBABILITY OF FAILURE FOR A GIVEN STRENGTH DISTRIBUTION

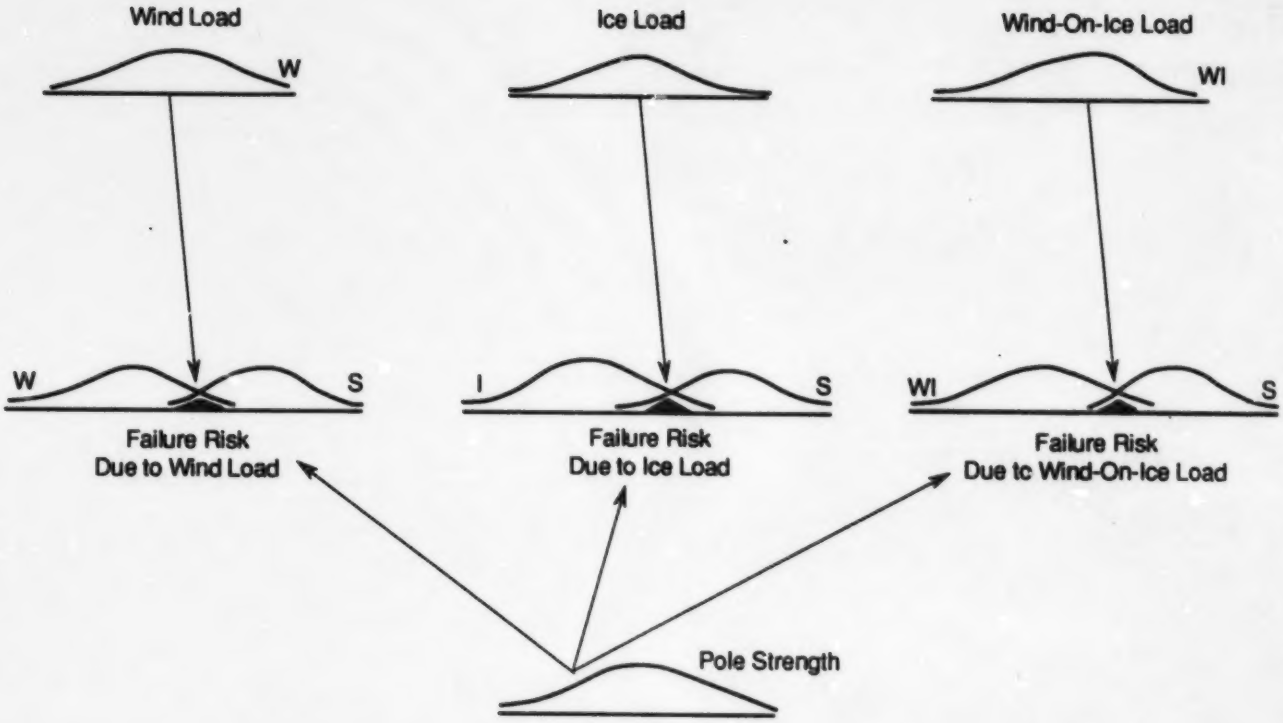


FIGURE 3

SCHEMATIC SHOWING THE CALCULATIONS OF FAILURE RISKS FOR VARIOUS LOADING CONDITIONS (NOTE: THE DASHED AREA ONLY INDIRECTLY REPRESENTS THE PROBABILITY OF FAILURE)

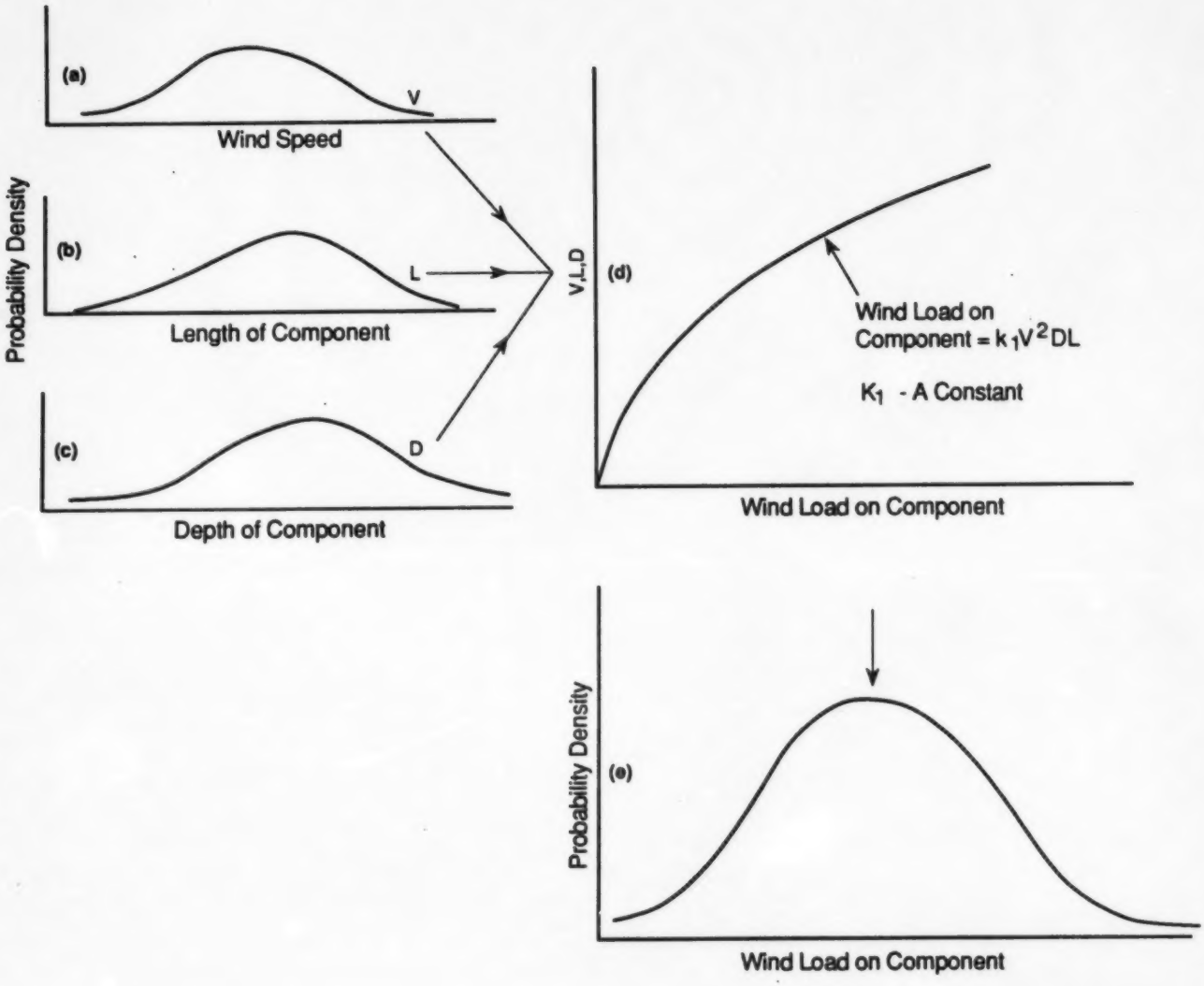


FIGURE 4

TRANSFORMATION OF WIND SPEED AND COMPONENT SIZE DISTRIBUTIONS INTO WIND LOAD DISTRIBUTION

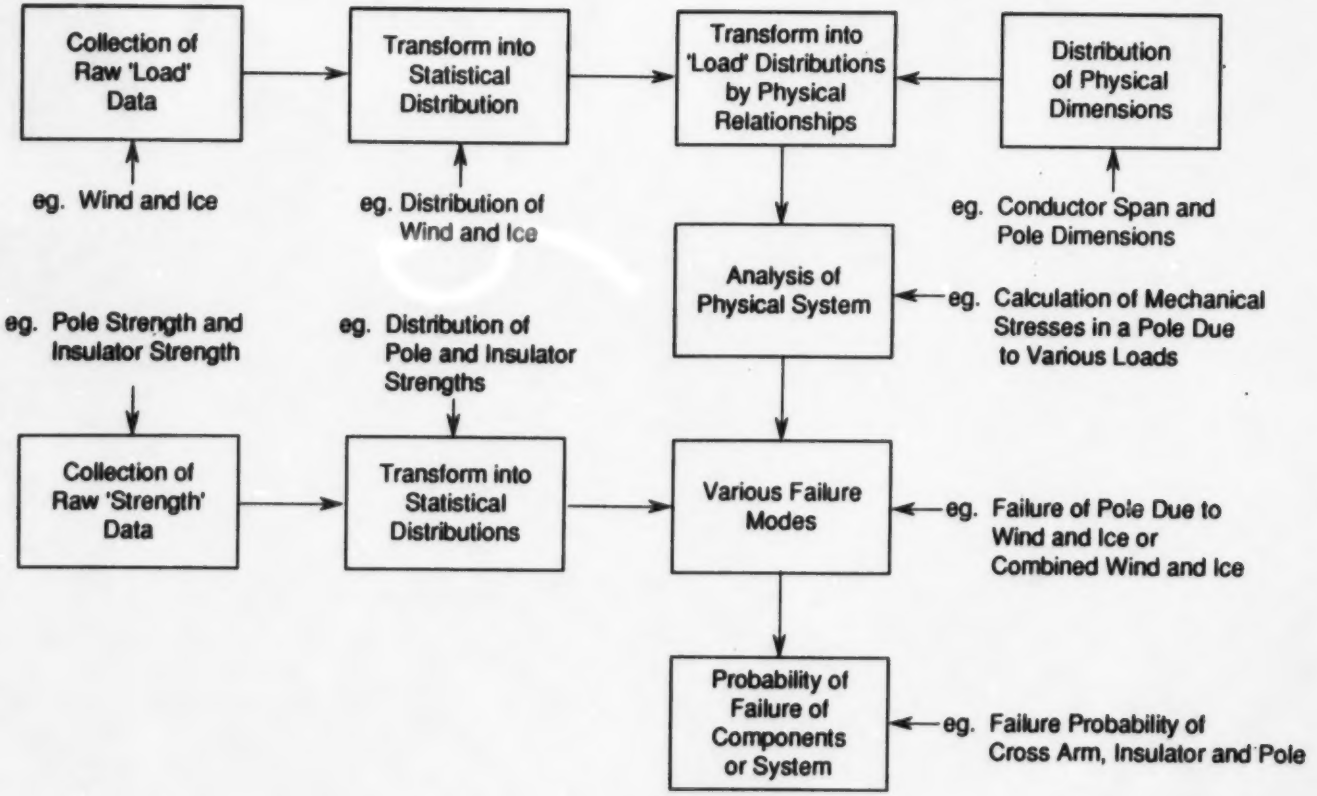

Collection of Raw 'Load' Data
Transform into Statistical Distribution
Transform into 'Load' Distributions by Physical Relationships
Distribution of Physical Dimensions
eg. Wind and Ice
eg. Distribution of Wind and Ice
eg. Conductor Span and Pole Dimensions
Analysis of Physical System
eg. Calculation of Mechanical Stresses in a Pole Due to Various Loads
eg. Pole Strength and Insulator Strength
eg. Distribution of Pole and Insulator Strengths
Collection of Raw 'Strength' Data
Transform into Statistical Distributions
Various Failure Modes
eg. Failure of Pole Due to Wind and Ice or Combined Wind and Ice
Probability of Failure of Components or System
eg. Failure Probability of Cross Arm, Insulator and Pole

FIGURE 5

TYPICAL STEPS REQUIRED IN APPLYING PROBABILISTIC METHODS TO POWER SYSTEMS

186914-L21-RD

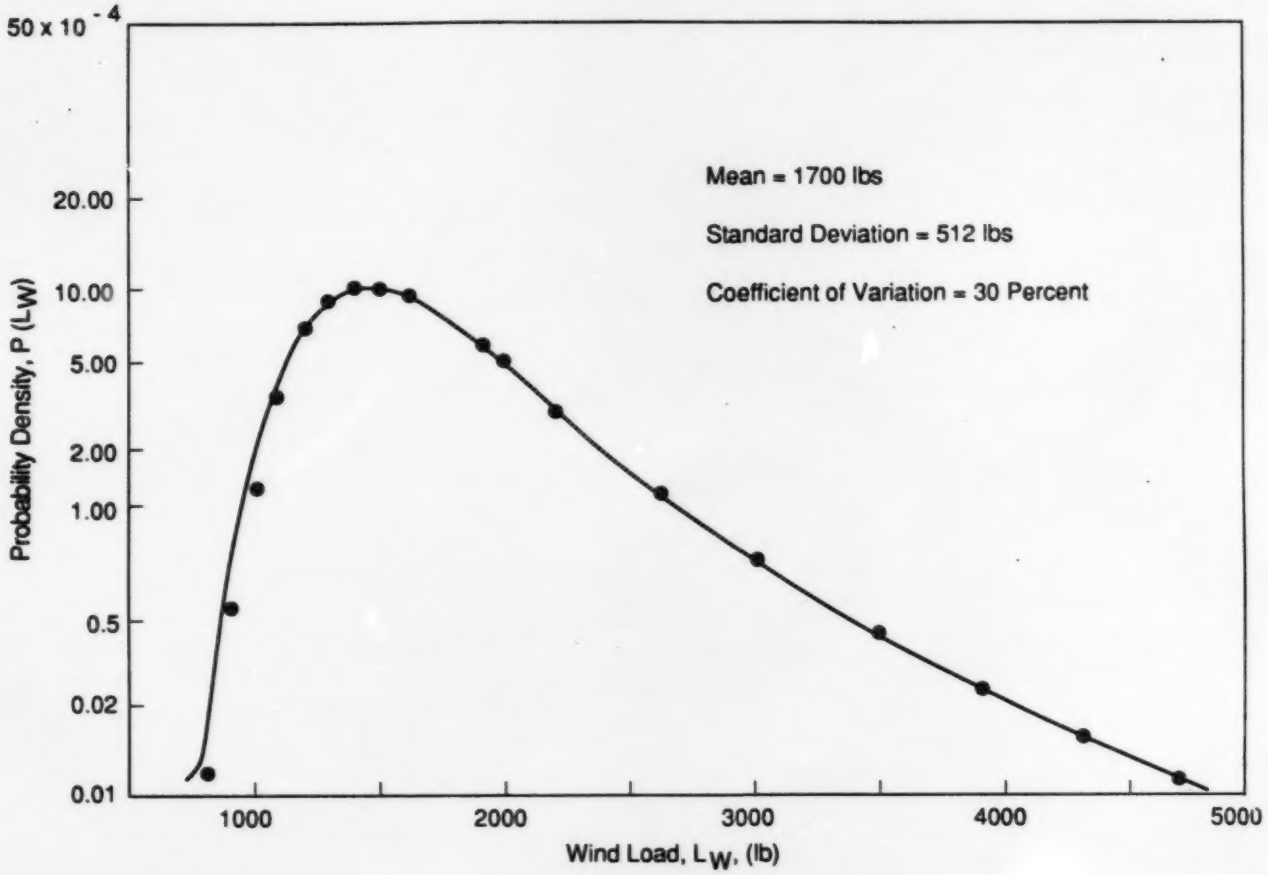


FIGURE 6

TYPICAL WIND LOAD PROBABILITY DENSITY FUNCTION

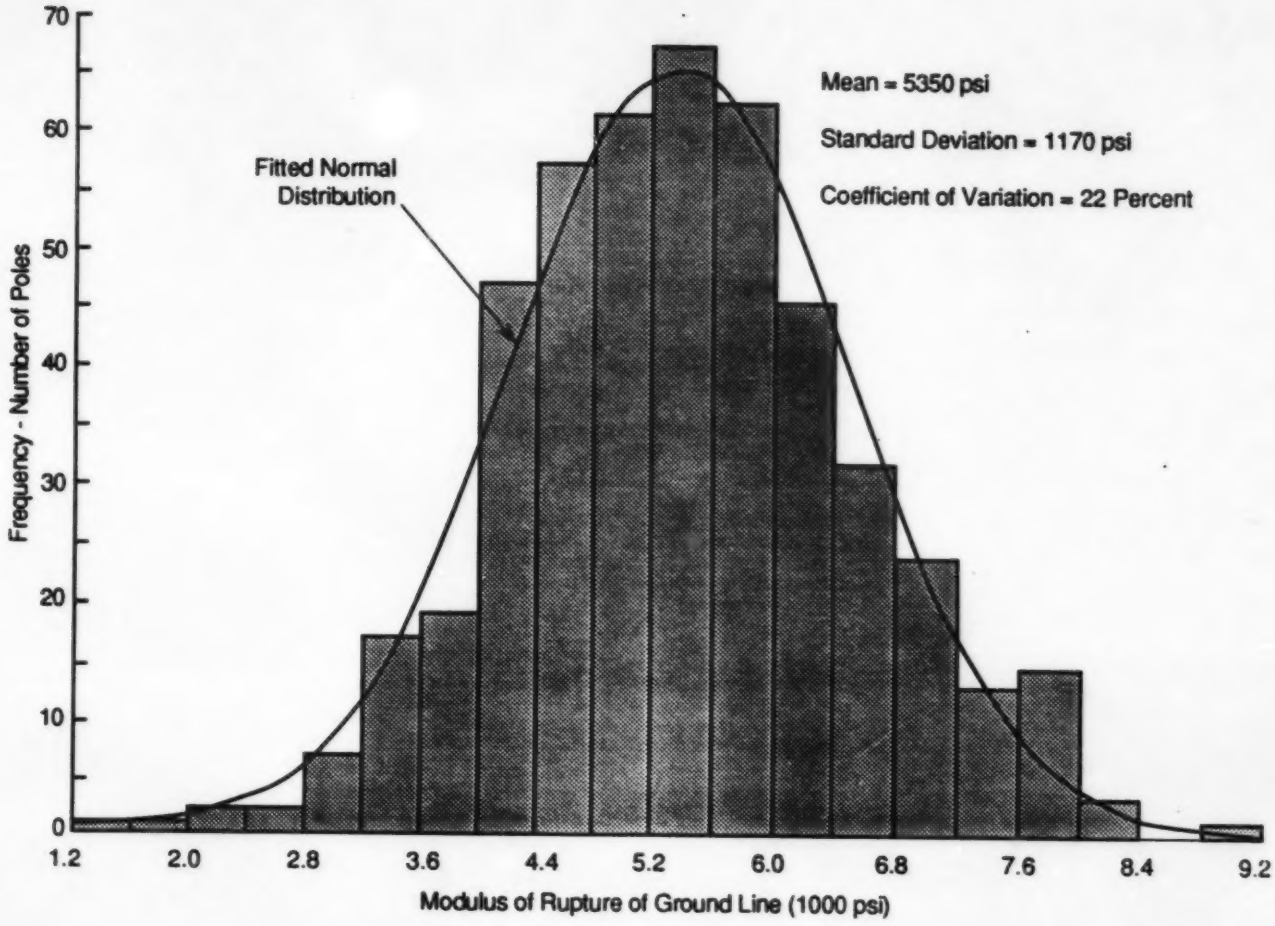


FIGURE 7

STRENGTH DISTRIBUTION FOR WESTERN RED CEDAR POLES (FROM EPRI REPORT "PROBABILITY BASED DESIGN OF WOOD TRANSMISSION STRUCTURES")

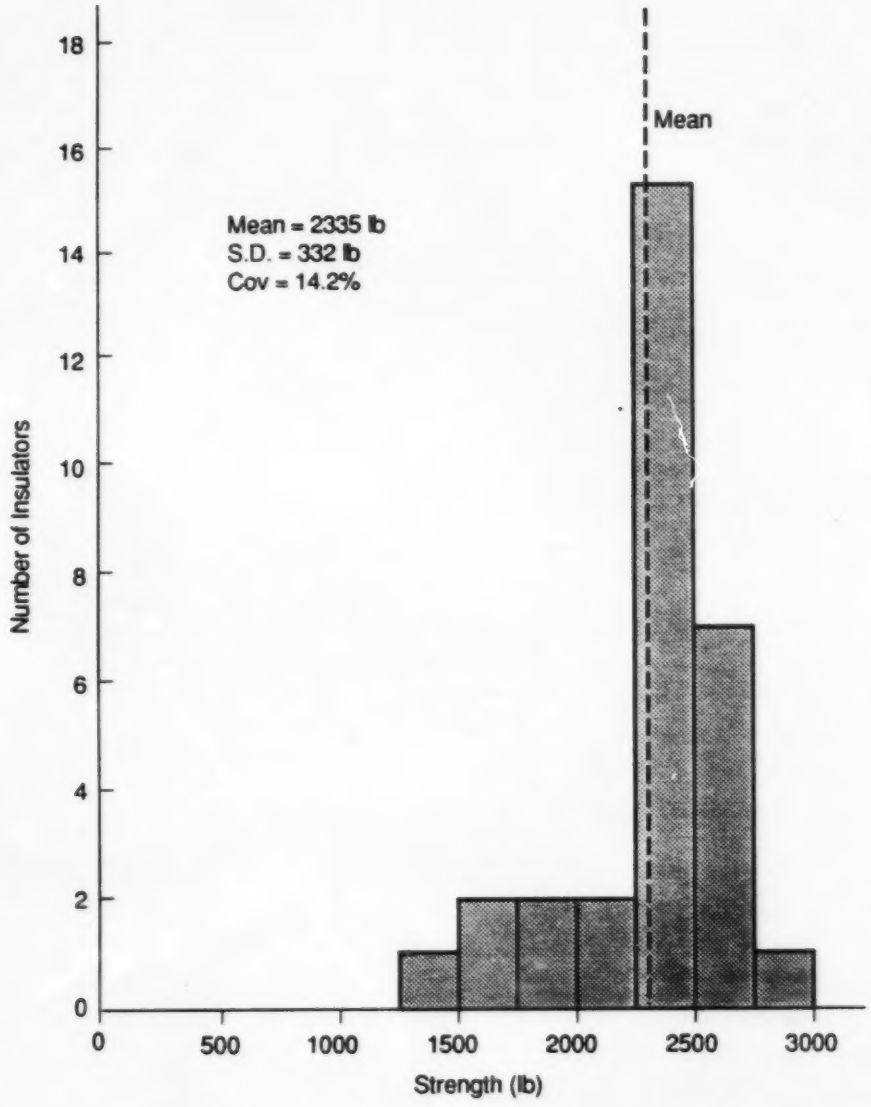


FIGURE 8

CANTILEVER STRENGTH OF POST INSULATORS

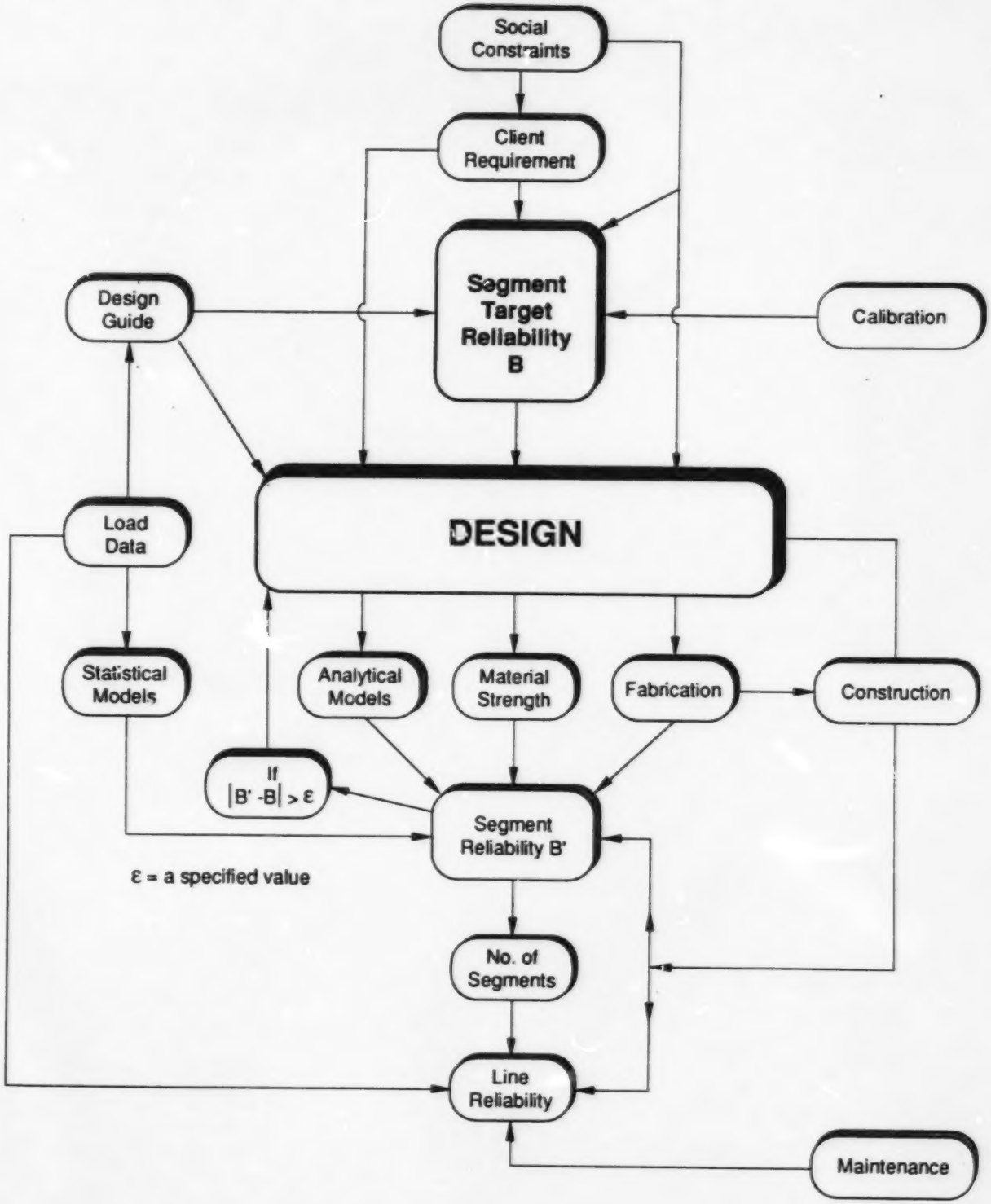


FIGURE 9

FLOW CHART OF PROPOSED RBD PROCEDURE

187468-L24-RD

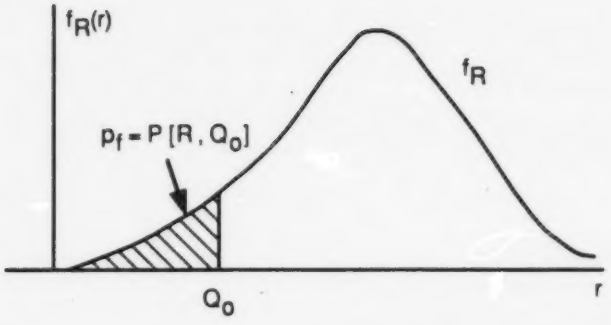


FIGURE 10(a)

JOINT PDF, $Q_f = F_R(Q_0)$, FOR A SINGLE RANDOM VARIABLE ($Q = Q_0$)

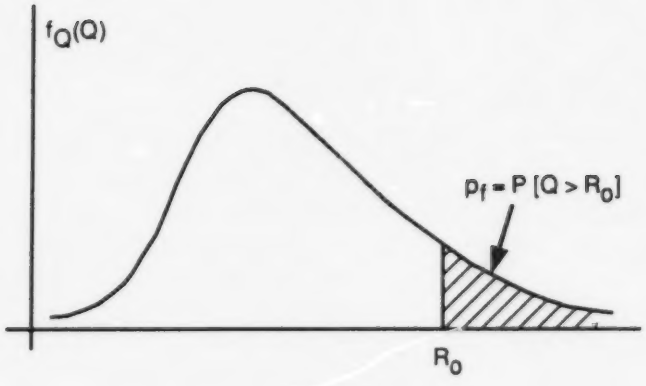


FIGURE 10(b)

JOINT PDF, $P_f = 1 - F_Q(R_0)$, FOR A SINGLE RANDOM VARIABLE ($r = R_0$)

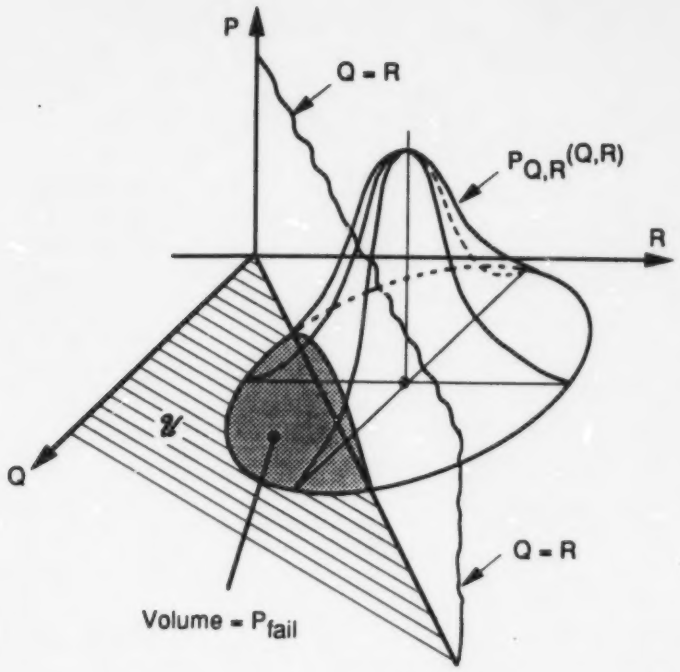


FIGURE 11

PROBABILITY OF FAILURE OF TWO RANDOM VARIABLES (FROM REF [15])

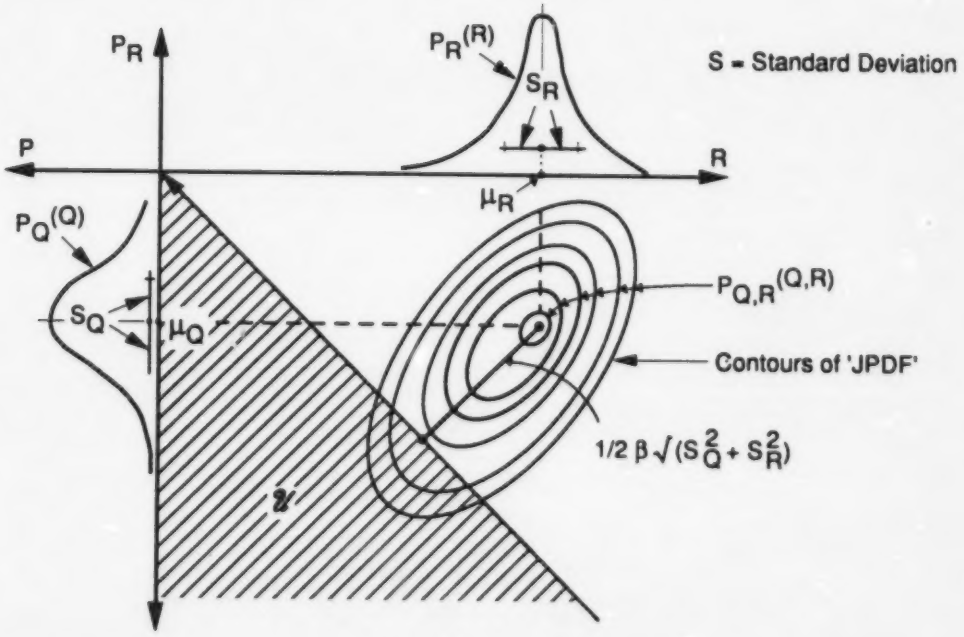


FIGURE 12

A SIMPLIFIED REPRESENTATION OF P_f FOR TWO RANDOM VARIABLES (FROM REF [15])